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Title: DESIGN OF A DIFFERENTIAL RADIOMETER FOR ATMOSPHERIC RADIATIVE FLUX MEASUREMENTS

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Design of a differential radiometer for atmospheric radiative flux measurements

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ABSTRACT

The Hemispherical Optimized NEt Radiometer (HONER) is an instrument under development at the Los Alamos National Laboratory for deployment on an unmanned aerospace vehicle as part of the Atmospheric Radiation Measurements (ARM/UAV) program. HONER is a differential radiometer which will measure the difference between the total upwelling and downwelling fluxes and is intended to provide a means of measuring the atmospheric radiative flux divergence. Unlike existing instruments which measure the upwelling and downwelling fluxes separately, HONER will achieve an optical difference by chopping the two fluxes alternately onto a common pyroelectric detector. HONER will provide data resolved into two spectral bands; one covering the solar dominated region from less than 0.4 micrometer to approximately 4.5 micrometers and the other covering the region from approximately 4.5 micrometers to greater than 50 micrometers, dominated by thermal radiation. The means of separating the spectral regions guarantees seamless summation to calculate the total flux. The fields-of-view are near-hemispherical, upward and downward. The instrument can be converted, in flight, from the differential mode to absolute mode, measuring the upwelling and downwelling fluxes separately and simultaneously. The instrument also features continuous calibration from on-board sources. We will describe the design and operation of the sensor head and the on-board reference sources as well as the means of deployment.

INTRODUCTION

Accurate broad band radiometric measurements are the key to understanding of atmospheric radiative transfer processes. The goal of the Atmospheric Radiation Measurements Program (ARM) is to understand these processes through long-term measurements at selected sites, intensive operating campaigns, and collaboration with other organizations. The measurements are used to test and improve models, with the ultimate goal of improving the Global Circulation Models (GCMs) which attempt to describe the Earth's climate and its evolution.

The concentration of ARM measurements is for ground-based measurements at the Cloud and Radiation Testbed (CART) sites, though there is the additional, evolving component of a long-term airborne monitoring capability by means of Unmanned Aerospace Vehicles through ARM/UAV. Accurate data are important here, in that the net radiation in a volume is deterministic for the local heating (cooling) of the atmosphere. As a measure of the sensitivity, GCMs estimate that for a global average change of 3-4 W/m^2 in net flux, temperatures will change by 1-2 degrees. This net flux change is roughly the equivalent of doubling atmospheric CO_2, and so it is important for a global measurement, to achieve accuracies in data and modeling that are much better than this. However, individual processes can have much larger local effects. For example, clouds have effects on the radiative balance at levels of typically many tens of W/m^2. Thus, progress can, and has been made with measurements of lesser accuracy.

The present state of measurements, however, requires improvement to achieve the next steps in understanding radiative transport. Common presently used instruments include pyrgeometers and pyranometers, which each attempt to measure the flux over a hemispherical field of view in the infrared and solar spectral regions respectively. Thus, one can measure the upwelling and downwelling fluxes in the two spectral regions using combinations of these instruments, and take appropriate combinations of these individual measurements to derive, say, the net flux at a location, or, extending further, obtain the flux divergence between two vertical levels by subtraction of the net fluxes. The calibration of these instruments are good, in an absolute sense, to +/- 3.5 percent at best, with seven percent being typical according to results quoted by NREL. Indeed, in a round robin calibration of a particular pyrgeometer by a number of reputable calibration labs, the spread in calibration values was eighteen percent. Furthermore, the typical rate of change in calibration values for some tested instruments is of order one percent over a day. When one propagates the quoted errors through a computation of flux divergence, one finds an rms uncertainty of tens of W/m^2 in typical scenarios.

Many details of instrumentation need to be considered to make significant improvements in this situation. One would ideally like to directly measure both the up- and down-welling fluxes and the differential flux with superior accuracy, and with minimal sensitivity to spectral differences, with excellent stability, and at a reasonable cost. Calibration accuracies must be improved, and, clearly, a measurement scheme relying on precision over absolute accuracy is to be preferred, since achievable precisions are almost always better than achievable absolute accuracies.

The instrument which we describe here addresses the issues outlined. The central goal in producing HONER is to measure the differential flux at a given location with excellent accuracy. We have set the design goal at 3% accuracy with a 1 watt per square meter threshold. The instrument is primarily intended for use on an aircraft though ground and satellite derivatives can be produced based on the same design philosophies. In addition to measuring net fluxes, HONER can be used to measure the individual up- and down-welling fluxes.

The HONER design uses the following key ingredients: 1. An integrating sphere geometry to ensure uniform responsivity; 2. Use of bulk materials rather than filters for ruggedness and stable selection of wavelength ranges; 3. Optical subtraction of signals to obtain net fluxes directly; 4. AC detection for common mode rejection; 5. Internal reference system traceable to NIST references

CONFIGURATION

HONER comprises two integrating spheres, each of which is shown schematically in Figure 1. Each sphere has two input apertures; one looking downward and the other upward. Radiation entering the input apertures is propagated into the sphere by means of an inverted compound parabolic concentrator (CPC). The geometry of the input apertures is such that the instrument has a 170 degree field-of-view; the remainder being obscured by structure surrounding the aperture. The radiation through each aperture is chopped at the same frequency, approximately 20 Hz, but out of phase. The phase relationship determines the operating mode and will be discussed later. One sphere is lined with Spectralon, Labsphere Inc.'s trade name for a diffuse reflecting material which provides uniform throughput from the UV to wavelengths up to 1.5 μm. The other is coated with a lambertian gold, also proprietary to Labsphere, to provide uniform throughput at all wavelengths longer than 1 μm. The total hemispherical reflectance of Spectralon and gold are plotted in Figure 2. The Spectralon provides sensibly flat reflectance from the UV to nearly 2 μm and the gold provides flat reflectance at all wavelengths longer than the visible region.

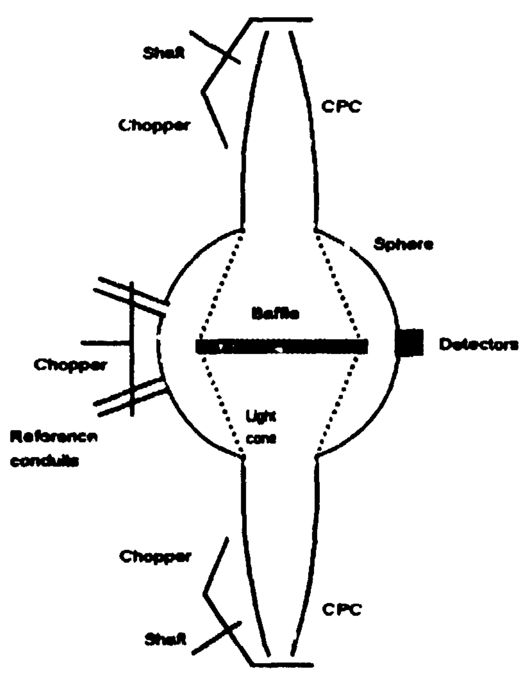

Figure 1. Schematic diagram of HONER showing all essential components.

Each sphere also contains two channels of pyroelectric detectors and each channel uses distinct filters. To aid in achieving insensitivity to the direction of arrival of the incident radiation, each channel will comprise four detectors distributed at 90 degree intervals about the sphere's equator. In the interests of spectral uniformity, reproducibility, stability, and low cost, the filters will consist of uncoated silicon and water free fused silica. The transmittances of the silica and silicon filters are shown in Figure 3. Thus, the filters define spectral bands of each channel as summarized in Table 1.

Table 1: HONER Signal Channels

Channel	Sphere	Filter(s)	Band
SW1	Short wave	SiO_2	UV-4.5 μm
SW2	Short wave	SiO_2 + Si	1.2-4.5 μm
LW1	Long wave	Si	1.2->50 μm
LW2	Long wave	SiO_2 + Si	1.2-4.5 μm

Channel SW1 provides uniform response to radiation in the wavelength from the UV to the silicon band gap at 1.2 microns. There is also a response to radiation from 1.2 microns to the silica cut-off at approximately 4 microns but, due to the spectrally non-uniform response generated by the Spectralon reflectivity, this is unacceptable flawed. Channel SW2 responds only to the 1.2 to 4 micron band in a manner which, within a constant factor, is identical to the response of SW1. Therefore, by subtracting the properly scaled output of SW2 from the output of SW1, we have a good measure of the total irradiance at wavelengths shorter than 1.2 microns.

Channel LW1 provides a good measure of the total irradiance at all wavelengths longer than 1.2 microns and channel LW2 provides a good measure of the irradiance between 1.2 and 4 microns. Adding the information gained from LW2 to that obtained from the short wave sphere provides a measure of the irradiance in the solar dominated portion of the spectrum, from the UV to 4 microns. Subtracting LW2 from LW1 provides a measure of the irradiance in the thermal IR, 4 microns and longer.

The HONER integrating spheres serve as comparators between the unknown fluxes incident on the CPC apertures and reference fluxes generated by calibrated sources and delivered to the sphere by optical conduits and modulated by a third mechanical chopper. The short wave reference is used to test the response of the system to radiation at wavelengths shorter than approximately 4 μm. As both spheres respond to radiation in this range, both will be fitted with a short wave reference source. The long wave reference source is used to test the response of the system to radiation at wavelengths longer than approximately 4μm, a spectral region to which only the long wave sphere is sensitive. Therefore, only it will be fitted with a long wave reference.

The short wave reference source is a 2.5 watt, quartz halogen lamp (Welch-Allyn model 01243) rated at 36 lumens output. The mean lifetime of these lamps is insufficient to

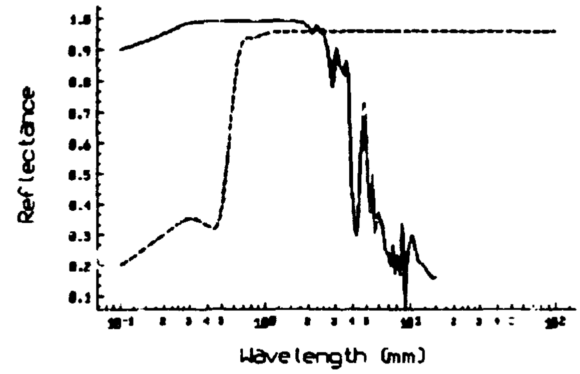

Figure 2. The total hemispherical reflectance of Spectralon (solid) and gold (dashed) showing the regions of sensibly flat response.

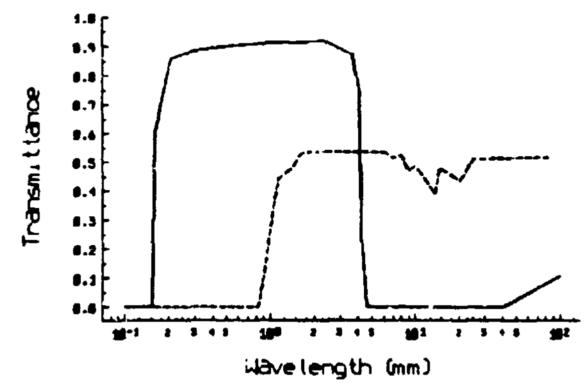

Figure 3. The transmittance of the materials used for spectral filtering of the data channels in HONER, 1.0 mm thick silica (solid) and 0.5 mm thick silicon (dashed).

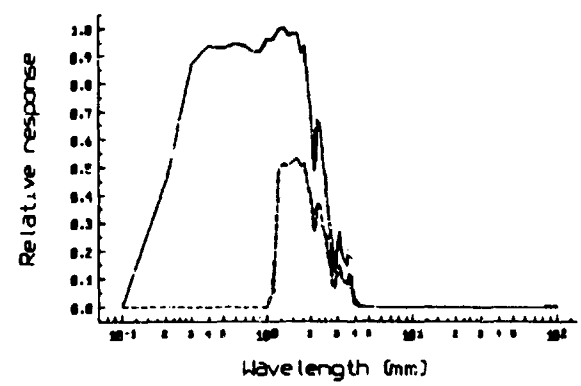

Figure 4. The relative spectral response of the data channels in the short wave sphere, SW1 (solid) and SW2 (dashed).

guarantee operation over a 48 hour mission. Therefore, we have mounted four, one operating and three spares, in a 5 cm diameter integrating sphere; that arrangement negating the geometric effects of lamp position. The output of this lamp is modulated by a third chopper blade at approximately 30 Hz but exactly 1.5 times the main chopper frequency and delivered to the main integrating sphere of each sensor system. We monitor the output of the lamp with two silicon photodiodes (Hamamatsu series S1337) in the main integrating sphere; the first is filtered with two millimeters of Schott BG28 color glass and the other is filtered with two millimeters of Schott RG850 color glass. The components of these photodiode signals which are synchronous with the 30 Hz chopper, are measured by separate lock-in amplifiers. The ratio of these signals determines the filament current. Thus, we control the output of the lamp to a constant color temperature. With the color temperature stabilized, we use the output of either of the photodiodes as an indicator of the total flux delivered by the reference source. While this source provides us with a known radiance by which we determine the slope of the responsivity curve, the intercept is known to be zero because the design of the choppers forces the admitted flux to zero when the aperture is closed.

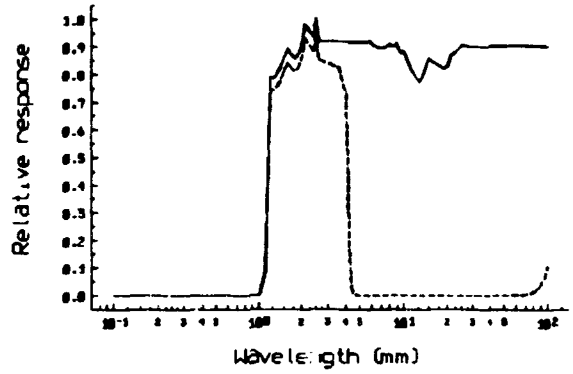

Figure 5. The relative spectral response of the data channels in the long wave sphere, LW1 (solid) and LW2 (dashed).

The long wave reference, used only on the long wave sphere, comprises a small, dark body emitter. The propagation path for the emitted radiation is also through the 30 Hz chopper but at such a location as to cause the modulation to be 90 degrees out of phase from the short wave reference radiation. The chopper blade is also a dark body emitter, operating at a temperature similar to that of the integrating sphere and which is monitored to within 0.1 K. The temperature of the reference source will be held at either 330K or 30K above the blade temperature, whichever is less. Thus, the long wavereference radiation is modulated between two known levels.

When HONER is operating in the absolute mode, the intercept of the long wave responsivity curve is the self-emission of the integrating sphere which is reflected back into the sphere when the entrance aperture is closed by the main chopper. In the differential mode, this quantity cancels from the analysis and the intercept is zero. It does, however, form the basis of the requirement that the temperature of the long wave integrating sphere be known with high accuracy. We will construct the sphere with a quarter inch aluminum wall to reduce gradients and measure the temperature using several thermistors. By this means, we expect to know the radiation temperature within 0.1K.

HONER will be flown with open apertures. This leaves the instrument at risk to thermal perturbaations caused by net air flows through the spheres. Domes over the apertures were rejected because their emission would be chopped and treated as a contribution to the atmospheric flux. Windows at the entrance aperture but inside the choppers were rejected due to the sensitivity to angle of arrival and polarization. However, a window at the internal aperture, the junction of the CPC and the integrating sphere, represents a compromise between the risk of air flows and the optical effects. As the maximum angle of incidence on a window at the internal aperture is 17.5 degrees, the sensitivity to angle of incidence and polarization are reduced. As the short wave sphere requires a silica filter for both channels, we will use a silica window at the internal aperture. That also introduces a requirement for a silica window in the path of the radiation from the short wave reference source for this sphere. Similarly, as the long wave sphere requires a silicon filter for both channels, we will use a silicon window at the internal aperture and silicon windows in the paths of the radiation from each of the reference sources.

SIGNAL MULTIPLEXING

The main aperture choppers, with two apertures on each blade, will operate at approximately 20 Hz but either 90 or 180 degrees out of phase. When these choppers are 90 degrees out of phase, HONER will be operating in the absolute mode making independent measurements of the upwelling and downwelling irradiances. When these choppers are 180 degrees out of phase, HONER will be operating in the differential mode measuring the difference between these irradiances. The third chopper, modulating the reference fluxes, will operate at a frequency precisely 1.5 times that of the main choppers. This will be achieved by operating the blade, having three apertures, in mechanical synchronization with the other two. The position of the conduits from the short wave and long wave references on the long wave sphere will mechanically constrain these signals to be chopped 90 degrees out of phase.

Lock-in amplifiers have the property of isolating the sine and cosine components at a particular frequency out of an input signal comprising a multitude of Fourier components. Conceptually, it is easiest to think of each of the HONER detector channels as being demultiplexed by two, 2-phase, lock-in amplifiers. In fact, the output of each detector channel will be digitized 128 times during each data acquisition window of 0.8 seconds duration and stored for post mission processing. The processing will involve digital simulation of lock-in amplifiers by using a fast Fourier transform.

When the choppers at the two input apertures are 180 degrees out of phase, the flux on the detectors is a square wave whose amplitude is the proportional to the difference between the irradiances on the upward-looking and downward-looking apertures. When these choppers are 90 degrees out of phase, the detector output, in response to the upwelling and downwelling irradiances, is the superposition of two periodic functions whose fundamentals are proportional to the sine and cosine, respectively, of 20 Hz. The detector response to the reference fluxes on the long wave sphere is the superposition of two periodic functions whose fundamentals are proportional to the sine and cosine, respectively, of 30 Hz. On the short wave sphere which has only a short wave reference, one of these components is absent.

DEPLOYMENT

An obvious necessity for any aircraft borne instrument having two near-hemispherical fields-of-view is that the aperture separation must be sufficient to exclude the aircraft from the fields-of-view. HONER will be carried by a Perseus B, unmanned aircraft which is produced by Flight Sciences Corp. One sensor head will be carried in the nose of each under-wing fuel pod. With an aperture separation of 61 centimeters, the aircraft obscures only 1.7% of both, 170 degree fields-of-view.

The basic HONER concept does not include the CPCs; the apertures admit the incident radiation directly into the integrating spheres. This, however, requires that the sphere diameter equal the aperture separation. The impetus for adding the CPCs is to reduce the sphere diameter with a corresponding reduction in the weight. As the temperature of the spheres must be maintained above the dew point, a reduction in the total surface area also reduces the required power. An additional benefit of using the CPCs is that, due to conservation of the Lagrange invariant, radiation incident on the entrance aperture over a near-hemispherical field-of-view enters the sphere within 17.5 degrees of the instrument's axis. A baffle is required along the axis to prevent direct propagation of flux from one aperture to the other. By making this baffle large enough to subtend the 17.5 degree cone, all radiation entering the sphere is uniformly forced to experience an initial reflection at the baffle. That this will aid the design goal of insensitivity to varying direction of arrival.

DATA ACQUISITION

Data from the signal channels on each sphere will be strobed onto 12 bit A/D converters synchronously with timing marks on one of themain chopper blanes. Thus, the phase angle for each datumwill be known precisely and the phase interval will be uniform. The two spheres will operate asynchronously. We will acquire 128 data from each channel over 8 revolutions of the 20 Hz chopper, approximately 0.8 second. During the next 0.2 second, we will acquire all state-of-health and housekeeping data and fire the aircraft beacon strobes. Light from the strobes, reflected by nearby clouds and aerosols, cannot be allowed to enter the measurements.

CALIBRATION

The results obtained from a precision radiometer are necessarily limited by the accuracy of the calibrations. HONER will be calibrated at Los Alamos using a procedure which is not yet fully defined. We possess and use calibrated sources and reference detectors which cover the spectral region from the UV through the thermal IR. Each of the devices which we will use as the basis for the HONER calibration has a 3σ accuracy of 1% or better, demonstrated by procedures tracable to NIST standards. The issues which will be addressed in the calibration process are absolute response to collimated and diffuse irradiances, sensitivity to variations in direction of arrival, equivalence of the two entrance apertures, sensitivity to variations in wavelength, and sensitivity to polarization.

SUMMARY

By implementing the concept of differential radiometry in HONER, we have designed an instrument which will provide improved measurements of atmospheric heating due to radiative flux. Work is continuing, in both modeling and testing, to determine the accuracy with which HONER's measurements in both the absolute and differential modes. We will complete a fully calibrated prototype of HONER by the middle of 1995 and the first mission is scheduled for November, 1995.

ACKNOWLEGMENTS

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